

## Modeling Strength Data for CREW CHIEF

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## ABSTRACT

The Air Force has developed CREW CHIEF, a computer-aided design (CAD) tool for simulating and evaluating aircraft maintenance to determine if the required activities are feasible. CREW CHIEF gives the designer the ability to simulate maintenance activities with respect to reach, accessibility, strength, hand tool operation, and materials handling.

While developing the CREW CHIEF, extensive research was performed to describe workers strength capabilities for using hand tools and manual handling of objects. More than 100,000 strength measures were collected and modeled for CREW CHIEF. These measures involved both male and female subjects in the 12 maintenance postures included in CREW CHIEF. This presentation describes the data collection and modeling effort.

## INTRODUCTION

Early identification of potential design-induced maintainability problems is essential to correct a problem before mock-up, fabrication, or production. To facilitate early identification of design problems, the Harry G. Armstrong Aerospace Medical Research Laboratory (AAMRL) and the Air Force Human Resources Laboratory (AFHRL) have developed CREW CHIEF, a computer-aided design (CAD) model of an aircraft maintenance technician.

Approximately 35 percent of the lifetime equipment cost and one-third of all manpower is spent on maintenance. Excessive repair time is caused by failure to adequately consider maintenance demands. The maintenance technician will spend hours making a repair which could have been completed in minutes with better accessibility. The CREW CHIEF model will reduce the incidence of such problems by allowing the designer

to perform maintainability analyses and correct design-related defects. Ultimately, not only will development engineering costs and acquisition time be reduced, but also life cycle costs and maintenance time while system availability grows.

Accessibility is a major problem in maintenance. Objects being maintained do not usually have the faulty components located for the convenience of the maintenance technician. Anything can fail, and eventually does if its used long enough. So virtually every detail of every component is a candidate for maintenance. Equipment designers attempt to place the high failure rate items in more accessible locations, but the function of the component usually takes precedence in determining location. Also, when new equipment is being designed, the failure rates for components are only estimates, and these estimates sometimes turn out to be far from accurate. The result is that high failure rate components are sometimes in inaccessible locations.

This results in "work arounds", where the maintenance technician is forced to work in uncomfortable and inefficient postures, such as kneeling, bending, squatting, prone, supine, lying on the side, or sitting on the ground. These are the "everyday" working postures for maintenance technicians. Because these postures are uncomfortable and less stable than standing or sitting in a chair, we can predict that they are less efficient. We can readily observe that the time required to perform a task in these "maintenance" postures is longer than the traditional postures of sitting or standing. We also know that the forces generated by the worker's strength will be less because of the less common directions of force and the less stable support for the body.

The body's ability to generate force varies greatly with the direction of force. A combination of gravity and body posture is the cause of this phenomenon. Most of our exertions tend to be performed with the trunk in a more or less erect posture and applying a force to overcome gravity, as in lifting and lowering of objects. The next most frequent activity involves pushing and pulling, that is, exerting a force away from or toward the body. Because we are mobile, we tend to avoid lateral force exertions. It is usually possible to "face" the work, so that lateral forces are minimized. These activities constitute most of what we define as manual materials handling. Tests confirm that the muscles produce relatively more force in these directions than in other less used postures and directions.

#### THE CREW CHIEF MODEL

CREW CHIEF, a computer-aided design (CAD) model of an aircraft maintenance technician which allows the designer to perform the functions of an expert ergonomist. The designer may simulate a maintenance activity on the computer generated image to determine if the activity is feasible. Expert system software automatically creates the correct body size and proportions for males and females, the encumbrance of clothing, personal protective equipment, and mobility. Physical access for reaching into confined areas (with hands, tools, and objects), visual access, and strength.

Version 1 of CREW CHIEF was completed in April, 1988. It incorporates several data bases, functional capability in 12 different maintenance postures, 1st to 99th percentile male and female dimensions, and 4 clothing types. Task analyses include flightline tools and manipulating components. Visibility and task interference analyses can be computed with this "electronic mock-up". More than 30 copies of CREW CHIEF software have already been released to aerospace companies. CREW CHIEF has already been used to support Air Force and Army programs. Version 2, almost complete, features an enhanced tool data base, tool envelop analyses, 3-D shaded surface enmeshment for the man-model, alternate populations, and animation.

To simulate the body postures typical in maintenance, CREW CHIEF provides twelve starting postures: standing, sitting, kneeling on one knee, kneeling on both knees, bending, squatting, lying prone, lying supine, lying on the side, walking, crawling, and

climbing. Some of these postures affect the mobility and strength available to perform the task. Appropriate evaluations of accessibility, reach, and strength analyses can be performed in each of these postures.

The CREW CHIEF program computes the strength capabilities of the maintenance technician based on gender, posture, and the task performed. CREW CHIEF computes strength for manual materials handling tasks (lifting, carrying, holding, pushing, and pulling), applying torque to bolts using wrenches, and connecting /disconnecting electrical connectors. More than 100,000 strength measurements were conducted to develop the strength analysis models in CREW CHIEF.

Accessibility analysis capabilities include the ability of the human-model to reach and operate any tool or object. The object, an electronics box for example, may already be part of the design. The CREW CHIEF program has 105 common hand tools to evaluate reach and accessibility.

#### STRENGTH RESEARCH

The largest single effort in the development of the CREW CHIEF human-model was gathering the research data. The CREW CHIEF human-model is a simulation of the physical characteristics and limitations of the maintenance technician. The development of this simulation requires an extensive and accurate data base describing those characteristics and limitations.

Table 1 shows combinations of variables and types of strength measured for the CREW CHIEF model development. More than 100,000 strength measures were made. An "x" indicates that a particular variable and type of strength variable was researched. In most cases the "x" represents a number of individual studies. For example, for the first combination of standing and tool torque, seven separate studies were performed with different combinations of other variables. Other combinations of variables included different sizes and lengths of wrench handles, different orientations of wrench handles and bolt heads, loosening and tightening exertions, different combinations of hands (right, left, or both), different types and sizes of wrenches, with and without gloves, different types and degrees of obstructing barriers, and extensions and U-Joint sockets.

A Sonic digitizer was used to measure body posture in many of the strength studies. Posture is an impor-

# VARIABLES TESTED FOR CREW CHIEF STUDY

VARIABLE	TOOL TORQUE	LIFT	PUSH & PULL	CARRY	HOLD & POSITION	CONNECTOR
GENDER	X	X	X	X	X	X
OBJECT HEIGHT	X	X	X		X	X
ORIENTATION	X	X	X		X	X
BARRIERS	X			X	X	X
HANDLE SIZE	X					X
ONE HANDED	X	X	X	X	X	X
TWO HANDED	X	X	X	X		
POSTURE						
STAND	X	X	X		X	X
SIT	X	X	X		X	
BEND	X	X	X	X	X	X
SUPINE	X	X	X			
PRONE	X	X	X			
SIDE	X	X	X		X	
KNEEL	X	X	X		X	
SQUAT	X	X	X	X	X	
WALK				X		
CRAWL			X	X		

TABLE 1. Combinations of variables and types of strength measured for the CREW CHIEF model development. More than 100,000 strength measures were made. An "X" indicates that a particular variable and type of strength variable was researched. The "X" usually indicates a number of individual studies were performed on a particular combination, with additional combinations of variables not shown in this table.

tant variable when shifting the center of body mass effects the force generated. For example, in pushing or pulling, the body mass may be shifted by bending or straightening the elbows. In one study of pushing strength, for example, men averaged 48 percent more and women 30 percent more when pushing with bent elbows versus straight elbows.

The sonic digitizer employs an array of microphones surrounding the subject. Electric spark gaps are taped to the subject's joint centers or other anatomical features useful in tracking posture. The sonic digitizer measures the time delay between the generation of the spark and when each of the microphones detect the popping sound of the spark. The delay is translated into a slant range distance, then the 3D coor-

dinates are computed. The sonic digitizer can locate points in 3D space at the rate of 48 Hz. By surrounding the subject with an array of 8 microphones, masking of body parts is eliminated.

Posture is critically important in all types of physical activities. It is especially important in maintenance tasks where the object being maintained often creates obstacles and forces the worker into restricted postures. When carrying for example, a low ceiling in a passage way or under the wing or fuselage of an aircraft can reduce the available strength, as shown in Table 2 below. The low ceiling (40% of stature) forces the worker into a bent posture, then a semi-squat, and finally crawling. At each progressive level, the amount of

weight that an individual can carry is reduced, until, in a crawling posture, it averages only 45 percent of the no restriction condition.

<u>CEILING HEIGHT</u>	<u>MALE</u>	<u>FEMALE</u>
UNLIMITED	153	79
80%	146	73
60%	113	54
40%	64	41

TABLE 2. Maximum weight (pounds) that can be carried in an 18 inch wide box with no handles while using two hands. The ceiling height was set to a percentage of stature. Values are averages.

The effect of posture on weight lift capability can be seen in Table 3. The values shown are the maximum weight (in boxes) people were able to lift from the floor and place on a shelf. The subjects were 50 men and 50 women. The maximum weight was determined using the incremental technique, increasing the amount of weight lifted until the subjects were no longer able to lift the box onto the shelf. Five postures were used: standing, kneeling, sitting, squatting, and lying on the side. All lifts used two hands, and the height of the shelf was adjusted to 35 percent of the subject's reach height in that posture, except for lying, where the shelf was ten inches high. The values are in pounds and averaged over each group of subjects.

<u>POSTURE</u>	<u>MALES</u>	<u>FEMALES</u>
Standing	118	58
Kneeling	99	53
Sitting	92	49
Squatting	79	43
Lying, side	42	21

TABLE 3. Maximum Weight Lift (Pounds) Capability for Different Postures. Maximum weight that can be lifted and placed on a shelf at chest height in a 24 inch wide box with no handles while using two hands.

The table shows the effective strength decreases when the body support becomes less stable. The kneeling

posture allows more mobility of the lower torso in adjusting the posture toward the load while still providing a stable support. Sitting provides a stable support but reduces the mobility of the lower torso, forcing the reach to shelf to be farther. The squatting posture has little support, as the subject is supported by the balls of the feet and must exert some effort to maintain balance. The lying on the side posture has little stability in the axis of load and requires the exertion of lateral forces to raise the weight.

A maintenance technician would prefer to work standing up. Often this is not possible because of constraints in the workplace. Obstructions limit the access, forcing a less than desirable posture.

Another example of the interaction of posture and direction of force is found in measures of torque produced with a socket wrench. In a study of isometric torque measured on 20 men and 20 women using a 1/2-inch square drive ratchet to turn a bolt with a 3/4 inch head, it was found that the least favorable location/orientation of a bolt head allowed only fifteen percent of the torque produced in the most favorable location/orientation.

Of course a maintenance technician would not choose the less favorable configuration, but may be forced to do so by obstacles. In another study measuring wrench torque, but where the subject had to reach over or around obstacles in the workplace, the available torque was reduced up to 80 percent due to the obstacles.

Ergonomics data is limited in supply and not familiar to most equipment designer. Designers typically think of the more ideal circumstances when considering the maintainability of a design. Furthermore, designers tend to overestimate the strength capabilities of the maintenance technician, especially failing to discount the strength due to awkward postures. If a significant portion of maintenance technicians are less strong than the designer imagines, impossible tasks may be inadvertently created.

#### MODELING STRENGTH

Many previous ergonomics models have failed to achieve their goal simply because model developers incorrectly assumed that all required data was available. There is a vast quantity of data available in the ergonomics literature, but most are not suitable for

development of a general purpose model. Most data are limited in the range of variables, the sample size, the applicability of the subjects to military populations, and non-availability of raw data for modeling. Developers of the Crew Chief model have programmed a large portion of their resources for ergonomics research. CREW CHIEF developers have gathered data regarding manual materials handling for the appropriate working postures, and torque strength capability for wrenches and electrical connectors. After the model development, these data will be submitted for inclusion in traditional military standards.

To overcome the limitations described above, a seven step testing and modeling procedure was developed for the CREW CHIEF program. Because of the complexity and the amount of research data needed for the CREW CHIEF model, it was not possible to gather all data on a representative sample of maintenance personnel. Rather, a benchmarking technique was developed to allow laboratory research to represent the population of workers. This seven step process insures that research data is representative of the population of Air Force maintenance personnel:

First, subjects were screened to represent the size and age of Air Force maintenance personnel. Since more than 99 percent of personnel doing manual work are age 30 or younger, research subjects were limited to the range of 18 to 30 years. The Air Force also has strict height and weight allowances defined by Air Force Regulation 160-43 which were also applied to research subjects. These restrictions may limit the utility of CREW CHIEF to represent older civilian populations, but Army and Navy personnel have almost identical characteristics.

Second, subjects were given benchmark strength tests. This battery of tests has been given to large samples of Air Force maintenance personnel over the years. One of these is the Maximum Incremental Weight Lift to Six Feet. This test is given to all Air Force and Army recruits and has been demonstrated to be highly correlated with manual materials handling tasks. Three static (isometric) strength tests are also given: the one-arm pull, which involves bracing the straightened left arm while pulling on a vertical handle with the right; the elbow height lift, which involves lifting against vertical handles positioned at elbow height; and the 38cm lift, which involves lifting with two hands against a horizontal

handle 38 cm above the floor. These tests have also been given to several thousand military personnel.

Third, the subject's body size is measured. For subjects tested at AAMRL, 69 measures were taken, for some of the tests made off-site, 20 measures were taken. These measures were made on several thousand military personnel.

Fourth, the subjects participated in simulated working tasks wherein their strength was measured. In most of these simulated work tasks, from 40 to 100 subjects were tested in each combination of variables. Treatments were randomized with suitable rest periods between all strength measures. Some treatment conditions were repeated at both the beginning and the end of each test session to verify the reliability of the subject's performance. The tool torque and push/pull tests were static (isometric) while the lifting, carrying, and holding were dynamic. Static measures were gathered with a computerized data collection system which evaluated the data against goodness criteria as it was collected and identified exertions to be repeated.

Fifth, the data were sorted, collated and edited. This process used both within subject and between subject relationships to identify outlying data values.

Sixth, the data were adjusted to represent the population of workers. This was accomplished using regression equations developed on large samples performing both the benchmark tests and some of the work tasks.

Seventh, the adjusted data were converted to algorithmic models for CREW CHIEF. When user of CREW CHIEF defines a task to be performed, the model determines which conditions apply, and select the appropriate strength models of male or female data. Predicted strengths for the 1st, 5th, 50th, 95th, and 99th percentiles are displayed on the workstation.

#### CONCLUSION

Most published ergonomics data are not suitable for development of a general purpose model because of limitations in the range of variables, the sample size, the applicability of the subjects to military populations, and non-availability of raw data for modeling. Developers of the Crew Chief model have developed an integrated procedure for defining data needs in terms of the tasks to be modeled,

selecting representative subjects, developing benchmarking techniques for matching laboratory data to population characteristics, analyzing and modeling the data, presenting data to designers in a comprehensive computer-aided tool.

CREW CHIEF developers have gathered data regarding manual materials handling for the appropriate working postures, and torque strength capability for wrenches and electrical connectors. These data have verified assumptions that posture and accessibility greatly limit the forces that can be generated by human strength and that posture and accessibility must be explicitly considered in the design of the maintenance workplace.

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